# BRIEF REPORTS AND COMMENTS

*This section is intended for the publication of (1) brief reports which do not require the formal structure of regular journal articles, and (2) comments on items previously published in the journal.*

# A note on flow rate and leak rate units

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The confusion in the literature and in the laboratory surrounding the terminology and units of gas flow rates, particularly as applied to calibrated leak artifacts, has prompted this discussion of leak rate units. Special attention is paid to conflicting usages of the term "throughput," and how this frequently leads to the loss of crucial information about the gas temperature and hence the true gas flow rate. The advantages of expressing leak rates in "mol/s," avoiding the complications of both the explicit mention of temperature in the unit and the need for agreement on "standard" temperature and pressure, are also discussed.

Upon initiation of a leak standards program at the National Bureau of Standards, we observed that the choice and proper use of units in which to express the flow of gas from a leak artifact and through a vacuum system are historically subjects of much confusion, stemming from problems with several of the definitions and usages of units in vacuum technology in general. While not attempting to cover the broader issues, we will discuss the various sources of confusion which apply to the immediate area of gas flow rate and leak rate units, and point out how use of the unit moles/second avoids most of the problems with the more commonly used units. We will show how different usages of the term "throughput" and its various associated units are ambiguous, frequently leading to loss of information about the gas temperature and hence, the gas flow rate. Other sources of confusion concerning leak rate and gas flow rate units, such as use of "standard" conditions in defining a unit, or the necessity to use multiple temperatures to characterize a leak artifact, will also be discussed. In many instances the errors caused by this confusion are inconsequential, but for high accuracy, high precision measurements the errors can be quite significant. The NBS Pressure and Vacuum Group intends to use the unit "mol/s" (moles/second) to report leak rates of calibrated leak artifacts (with gas species and temperature of the leak artifact separately stated), and believes that the rest of the calibrated leak user community can benefit from using this unit as well. For calibrated leak artifacts containing gas mixtures, the unit will be "mol/s" for each of the individual gas species.

Looking first at how the common usages of the term "throughput" lead to confusion in the expression of gas flow rate, consider the definition of "throughput" found in the American Vacuum Society *Dictionary of Terms*[1] (as well as numerous other places in the literature): "throughput—The quantity of gas in pressure–volume units, at a specified temperature, flowing per unit time across a specified open cross section." From this definition "throughput" and "gas flow rate" are inferred by some to be synonomous, and a typical "unit" of "throughput" is "atm cm$^3$/s at $T_1$ °C." This is most likely the original intent of the word "throughput." However, the literature also abounds with equations of the type[2,3]

$$Q = d/dt(PV), \tag{1}$$

where $Q$ is referred to as the "throughput," $P$ is the gas pressure, $V$ is the containment volume, and $(d/dt)$ indicates the time derivative, but the temperature is *not* specified. There are those who argue that it is "understood" that there is an implicit "at $T_1$ °C." Some understand $T_1$ to be "room temperature," whatever that may be, others 0 °C. The point here is that use of the word "throughput," as it is commonly used to describe gas flow in such an ambiguous fashion, either results in an ill-defined, implied temperature in the "unit," or encourages the dropping of the temperature from the "unit" altogether, resulting in an incomplete description of the molar or mass flow rate. That the description is incomplete can be seen from the expression for the molar flow rate for an ideal gas under isothermal conditions:

$$Q_m = Q/(RT), \tag{2}$$

where $Q_m$ is the molar flow rate, $Q$ is defined in Eq. (1), $R$ is the molar gas constant ($R = 8.314$ J mol$^{-1}$ K$^{-1}$ = 82.06 atm cm$^3$ mol$^{-1}$ K$^{-1}$ = 62.36 Torr l mol$^{-1}$ K$^{-1}$), and $T$ is the absolute temperature in Kelvins. Loss or misunderstanding of the temperature $T$ subsequently results in either the inability to calculate or the miscalculation of the molar flow rate. The use of the unit "mol/s" eliminates this problem, since the originator of the measurement, who knows the temperature $T$, must immediately incorporate this knowledge [using Eq. (2)] to express the flow rate in mol/s.

Even when properly used, "units" such as "atm cm$^3$/s at $T_1$ °C" can be a source of confusion if used to describe leak artifacts. In addition to the $T_1$ in the unit required to calculate mass or molar flow rate, the temperature $T_2$ at which the leak was calibrated and the temperature $T_3$ at which it is being used must also be known. Under such circumstances it is very easy for the three different temperatures to become confused. By expressing the flow rate in mol/s, the possibility for confusion is greatly reduced.

Another common practice with leak rate units is to express the leak rate in terms of "standard" conditions, such as "standard $cm^3/s$" or "$cm^3/s$ STP." Unfortunately, there exist several different usages of "standard conditions." If both the "standard pressure" and "standard temperature" are not explicitly stated, the units are ambiguous. Occasionally[4] a temperature and/or pressure *range* will be given for "standard" conditions. The consequences are not trivial for a helium diffusion leak, where a few degrees change in temperature can result in a few percent shift in the leak rate. Since it is quite unlikely that everyone will suddenly agree on what "standard" conditions are, we suggest that these units be dropped in favor of mol/s, which avoids the problem altogether.

To further demonstrate how the term "throughput" causes widespread confusion, note that the dimensions of Eq. (1) are those of [(force/area) × (volume)/(time)], or power, which are not the same dimensions as flow rate dimensions (mol/time). Accordingly, one occasionally sees in the literature the dimensions of power explicitly ascribed to the word "throughput,"[5] illustrating that not everyone automatically infers an implied temperature associated with Eq. (1). Strictly speaking, the quantity $Q$ in Eq. (1) *is* the power that is required to move a gas at constant flow rate and temperature across a specified cross section of a vacuum system, and can be of interest in certain areas of vacuum equipment design. (It is not the additional power that is carried by the gas across the cross section except in cases of adiabatic flow.) Thus, for those who use the word "throughput" to mean $Q$ in Eq. (1) at face value, the dimensions of power *are* appropriate. For those who use the word "throughput" to mean Eq. (1) "at a temperature," the dimensions of flow rate are appropriate. However, it is obviously not appropriate to use the word "throughput" to mean both of these quantities, since their dimensions are different, a point not generally recognized. Note that the "unit" "atm $cm^3/s$ at $T_1$ °C" is an unorthodox unit in the strictest physical and mathematical sense, since it does not have any well-defined dimensions on its own. It should perhaps be regarded instead as an *expression* whose meaning is given by a relationship such as Eq. (2), which has well-defined dimensions of molar flow rate. Use of mol/s at the outset indicates to the reader that if the word "throughput" is being used, it is being used in the sense of a flow rate.

Another important consideration is that the unit "mole" is recognized as the "amount of substance" in the SI system of units, so that mol/s is the natural SI unit of flow rate.

In summary, there are several reasons for preferring the unit mol/s over several other popular units for leak rate and gas flow rate. Foremost is that it avoids errors resulting from the failure to properly specify the temperature in "throughput" units, it also lessens the confusion of multiple temperatures associated with leak artifacts, and it avoids the confusion that sometimes exists with the term "standard" temperature and pressure. It also clarifies which usage of the word "throughput" is being used. Finally, mol/s is in accordance with the SI system of units.

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[1] *Dictionary of Terms for Vacuum Science and Technology, Surface Science, Thin Film Technology, Vacuum Metallurgy, Electronic Materials*, edited by M. Kaminsky and J. Lafferty (AIP, New York, 1980), p. 69.
[2] L. Holland, W. Steckelmacher, and J. Yarwood, *Vacuum Manual* (E. & F. N. Spon, London, 1974), p. 18.
[3] A. Roth, *Vacuum Technology* (North-Holland, Amsterdam, 1982), p. 67.
[4] American Vacuum Society Standards AVS 2.1, 1963 and AVS 2.2, 1968.
[5] J. F. O'Hanlon, *A User's Guide to Vacuum Technology* (Wiley, New York, 1980), p. 22.

# A study of target heating in low-energy ion-beam processing

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Precise control and knowledge of sample surface temperatures are of paramount importance when discerning the effects of ion-beam etching and low-energy ion implantation on the properties of semiconductors. Although many investigations have been carried out to study process-induced heating effects, they have concentrated primarily on deposition; viz., substrate temperature studies for evaporation techniques[1,2] and for rf and dc sputtering.[3] Temperature studies at an ion target, a surface being etched, and/or ion implanted in low-energy ion-beam processes, have been generally neglected in the literature. However, it is this surface which is of critical importance in ion-beam etching and low-energy ion implantation. This dearth of temperature measurements at surfaces subjected to low-energy ion beams is due, in part, to the high degree of difficulty associated with reliably obtaining such data. For example, thin-film thermo-

  